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Evaluation of diagnostic tools for naturally occurring lameness in swine

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Evaluation of diagnostic tools for naturally occurring lameness in swine

by

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Program of Study Committee:
Locke Karriker, Major Professor
Anna Johnson
Darin Madson

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

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DEDICATION

I would like to dedicate this thesis to my family. My upbringing on our family farm, Samson Family Farm, in southern Montana is the reason for my interest in the swine industry. Thank you for all your love and support!

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ABSTRACT

Sow lameness is a production disease affecting not only animal welfare but also swine profitability. Second to reproductive problems, lameness is a major cause for premature sow culling in the swine industry (Anil et al., 2005). It has been estimated that 32% of sows culled for lameness have only produced one litter (Boyle et al., 1998). Lameness has been estimated to cost the United States swine industry approximately $23 million/year (Butters-Johnson et al, 2011).

The overall goal of this thesis was to validate diagnostic tools using a naturally occurring sow lameness model. This work was completed through four objectives: 1) to determine if behavior assessments, mechanical nociceptive threshold testing and walking and standing lameness scoring could identify a lame sow, 2) to determine if behavior assessments, mechanical nociceptive threshold testing and walking and standing lameness scoring were affected by the body system suspected to be contributing to the lameness identified using the Swine Lameness Diagnostic Manual, 3) to determine lameness etiology within the suspected body system as guided by the Lameness Diagnostic Manual, 4) to evaluate the accuracy of the suspected lameness etiology using the results of the Swine Lameness Diagnostic Manual, standing lameness scoring, locomotion lameness scoring and swine veterinarian expertise.

The results of this thesis identified that the walking and standing lameness scoring systems and behavior are promising tools for a producer to use on farm for lame sow identification. However, behavior assessments, mechanical nociceptive threshold testing and walking and standing lameness scoring were less correlative when evaluating the body system suspected to influence lameness. The Swine Lameness Diagnostic Manual

was able to identify a presumptive lameness etiology for each case. However, a panel of practicing swine veterinarians unanimously agreed that the manual identified the correct and complete lameness etiology on only 4.3% of the cases after reviewing all data and diagnostic testing for each case.

CHAPTER 1. INTRODUCTION

The overall goal of this thesis was to validate diagnostic tools using a naturally occurring sow lameness model. This work was completed through four objectives: 1) to determine if behavior assessments, mechanical nociceptive threshold testing and walking and standing lameness scoring could identify a lame sow, 2) to determine if behavior assessments, mechanical nociceptive threshold testing and walking and standing lameness scoring were affected by the body system suspected to be contributing to the lameness identified using the Swine Lameness Diagnostic Manual, 3) to determine lameness etiology within the suspected body system as guided by the Lameness Diagnostic Manual, 4) to evaluate the accuracy of the suspected lameness etiology using the results of the Swine Lameness Diagnostic Manual, standing lameness scoring, locomotion lameness scoring and swine veterinarian expertise.

Sow lameness is a production disease affecting not only animal welfare but also swine profitability. Second to reproductive problems, lameness is a major cause for premature sow culling in the swine industry (Anil et al., 2005). It has been estimated that 32% of sows culled for lameness have only produced one litter (Boyle et al., 1998). Lameness has also been estimated to cost the United States swine industry approximately $23 million/year (Butters-Johnson et al, 2011). Several clinical lameness diagnostic tools have been successfully validated using a sow model of induced lameness. These tools include behavioral assessments, standing and walking lameness scores, kinematics, and mechanical nociceptive threshold tests (Mohling et al 2014a, Mohling et al 2014b, Karriker et al 2013). Further, in response to industry interest in a consistent diagnostic approach to lameness cases in the field, Karriker and colleagues (2014) created a comprehensive Swine Lameness

Diagnostic Manual that incorporates pre and postmortem assessments that guide the investigator to a list of differentials and diagnostic recommendations. This manual groups lameness etiologies into five systems: 1) central nervous system, 2) peripheral nervous system, 3) digestive/metabolic system, 4) musculoskeletal system, 5) integumentary system. The focus of this work was to test these resources on naturally occurring lameness cases to identify tools and resources that could be helpful for veterinarians in the field.

This thesis is presented in six chapters. Chapter two summarizes the previous research completed on lameness detection and evaluation methods, lameness etiologies, and diagnosis of lameness. Chapter three is the first research chapter and discusses the evaluation of standing and locomotion lameness scoring, behavioral assessments, and mechanical nociceptive threshold testing on naturally occurring sow lameness. The objectives of this study were to validate these diagnostic tools on naturally occurring lameness in sows and gilts. The hypothesis of this study was that these tools could successfully identify a lame sow. Chapter four is the second research chapter and discusses an evaluation of the Swine Lameness Diagnostic Manual. The Swine Lameness Diagnostic Manual included 5 decision trees, each representing a body system that may be affected in a case of lameness. The five body systems included: (1) central nervous, (2) peripheral nervous, (3) musculoskeletal, (4) integumentary, (5) digestive/metabolic. The objective of this study was to test the utility of the Swine Lameness Diagnostic Manual on natural lameness cases in sows and gilts. The hypothesis of this study was that the Swine Lameness Diagnostic Manual could successfully diagnose lameness etiologies in naturally lame sows and gilts. Chapter five describes the Sow Distal Limb Image Library, a web-based resource that highlights variations of sole, heal, toe, white line, and dew claw pathology observed on non-lame limbs of the commercial sows studied in Chapters three and four. The objective of this resource is to familiarize veterinarians and farm employees with the variations of foot appearance that can occur on non-lame sows but might be mistaken for true pathology. Individuals working through lameness cases may improve diagnostic accuracy and proper treatment of lameness cases if they look beyond the changes documented in the image library from non-lame sows and look further for the cause of lameness. Chapter six revisits the four objectives of this thesis and previous lameness research and recommends next steps in sow lameness research.

CHAPTER 2. LITERATURE REVIEW

Sow lameness is a production issue affecting not only animal welfare but also swine profitability. Second to reproductive problems, lameness is a major cause for premature sow culling in the swine industry (Anil et al., 2005). The swine industry has made production modifications to provide consumers with a pork product they demand while becoming more efficient by decreasing the amount of feed that it takes to produce the product. These modifications are likely contributing to the decrease in productive lifetime of breeding females in the industry (Stalder et. al 2004). Significant associations have been found between a herd's mortality status and prevalence of lameness (Abiven et al 1998). Clinical signs associated with lameness have also been found to increase the risk of involuntary culling (Jensen et al 2010). This chapter will discuss previous research completed on lameness detection and evaluation methods, lameness etiologies, and diagnosis of lameness. Lastly, we will identify gaps in our understanding of these topics.

Detection and Evaluation Methods

There are many detection methods discussed in the literature. There are subjective detection methods and objective methods. There are detection methods that are more or less practical for use in a field setting. Detection of lameness is the first step in management of lameness issues within a herd. The ultimate goals for research focusing on detection of swine lameness should be to improve the ability and timeliness of detection in the field and to identify genetic susceptibilities for breeding stock.

Detection methods discussed in the literature can be grouped into two categories: visual detection and automatic detection. Main and colleagues designed a visual scoring system to quantify lameness, focusing on behavior, standing posture, and the animals' gait.

The system was based on a 6-point scale and they found that there was 94% agreement between users (Main et al 2000). A second study used visual locomotive characteristic evaluation as well as the animals' conformation to determine their explanatory value on the occurrence and severity of osteochondrosis (OC). In this study, the authors found that swaying hindquarters and stiff gait were associated with greater OC scores (worse OC) in the femoropatellar and tarsocrural joints. Smaller medial claws (compared to the later claws) on the forelimbs was associated with lower OC scores in the femoropatellar joint. Steep and weak pasterns on the forelimbs had higher OC scores in the elbow joint. Lastly, steep and weak pasterns of the hind limbs were associated with lower OC scores in the tarsocrural joint (de Koning et all 2012). Visual detection and scoring methods are practical tools for use in a field setting. While detection is the first step toward diagnosis and management of lameness cases, they are not effective tools on their own.

Automatic, or more technically advanced detection methods include ear sensors for position and acceleration measurement (Traulsen et al 2016), kinematic motion capture using infrared cameras and reflective markers (Stavrakakis et al 2015), footprint analysis, lying-to-standing transition and foot lesion observation (Gregoire et al 2013), and force plate technology (Pluym et al 2013). An embedded microcomputer-based force plate system was developed to measure vertical forces of each limb and use sow weight distribution as an identifier of lame sows before clinical signs can be visually observed. Preliminary data suggested that this technology could identify lameness (Sun et al 2011). Traulsen and colleagues evaluated the use of ear sensors to collect position and acceleration measurements. The study found that these sensors could help describe the activity patterns of the sows but did not prove to be an effective, practical lameness detection system (Traulsen et al 2016). Using infrared cameras and reflective tape on the head, trunk and limb of pigs, Stavrakakis found vertical head displacement and asymmetric stride phase timing to be the best detector of lameness. This research also found that irregularity in the step-to-stride length ratio was elevated in young pigs that presented with lameness later in life (Stavrakakis et al 2015). Another study found by using a transportable force plate device and image processing, sows exerted less weight on their lame leg and mainly compensated their weight to the contralateral non-lame limb (Pluym et al 2013). In contrast, a study by Meijer evaluated the use of pressure mats to assess compensatory force distribution in lame pigs and found that lame animals showed a shift in loading toward their diagonal and contralateral limb (Meijer et al 2014). Mohling and colleagues evaluated the embedded force plate and the GAITFour gait analysis walkway system to objectively identify lameness though this study included an induced lameness vs. natural lameness model (Mohling et al 2014).

Other papers in the literature focus on combined detection approaches. Nalon recommends a “multidimensional” approach that including both visual and automatic detection systems such as kinematics, kinetics, and/or force plate technology because of the variation in clinical presentation between lame animals. (Nalon et al 2013). Gregoire and colleagues evaluated footprint analysis, kinematics, accelerometers, lying-to-standing transition and foot lesion observation in breeding swine. Lying-to-standing transitions was evaluated using a four-point scale: 1) animal stands up without hesitation; 2) animal takes more than 5 seconds to stand up; 3) animal shows hesitation, has to change position or lies down again before standing up; and 4) animal refuses to stand up or stays in a sitting position. The kinematics showed lame animals had slower walking speeds, shorter stride length and longer stance time. Accelerometer measurements found that lame sows spent less time standing over a 24-h period, laid down earlier after feeding and stepped more often during the hour after feeding. Visual observation of back posture showed 64% of lame sows had an arched back, though footprint analysis and lying-to-standing transition and foot lesions were not found to be successful (Gregoire et al 2013). Abell and others compared of the predictive abilities and accuracies of weight distribution and gait measures relative to one another and to visual lameness methods on induced sow lameness. They found that weight distribution measurements had a higher predictive ability than the gait measurements (Abell et al. 2014). Lastly, a study by Bertholle and colleagues investigated the use of radiographs, a visual lameness scoring scheme and a quantitative pressure-mat bases locomotion analysis system. The pressure mat system provided information about the pressure distribution pattern of a foot. This is in contrast to a force plate which measures ground reaction forces. Radiographs were able to detect subclinical lesions and the early repair process. The visual scoring and pressure mat showed weak correlation with OC lesions detected by histology (Bertholle et al 2016).

Detection is critical to the management of lameness in the swine industry. Early detection by producers and veterinarians in a field setting will have a strong influence on treatment and management success. Further, the ability to detect lameness characteristics that may have a genetic or heritable component at the seedstock level can have great implications. These needs suggest there may be a place for both detection methods with the more advanced, technical methods being used closer to the top of the genetic industry tree. However, in any situation or environment, detection is only the first step toward diagnosis and treatment.

Etiologies

The list of etiologies that has been described to contribute to lameness in swine is extensive. Research and anecdotal field reports suggest there is often more than one lesion/factor contributing to the lameness. The multifactorial nature of lameness combined with reports of prevalence ranging from 8.8% to 16.9% (Heinonen et al 2013), advocates for the investigation of effective detection and diagnostic methods. This section of the literature review will cover infectious and developmental etiologies, environmental factors including housing type, flooring type and feeding system, genetics, nutritional factors, and management effects associated with swine lameness.

Gross/Diagnostic

Swine-related OC has been the focus of many research studies. Schenck and Marchant-Ford found OC and foot lesions to be the primary cause for culling in growing and breeding swine (Schenck, Marchant-Forde 2018). Yrehus and colleagues discusses the multifactorial etiology of OC and while there is not believed to be one single factor accounting for all aspects of the disease, heritability, rapid growth, anatomic conformation, trauma and dietary imbalances are thought to contribute (Yrehus et al 2007). Another study by Ytrehus and colleagues investigated the effect of epiphyseal growth cartilage after interrupting the blood supply in the femur of growing pigs. They found that the loss of vascular supply caused chondronecrosis, similar to that of spontaneously occurring OC (Ytrehus et al 2004). In addition to OC (Dewey 1993), osteomalacia, osteoporosis, osteoarthritis, arthritis (Dewey 1993, Engblom et al 2008, Kirk et al 2005), leg weakness, foot rot, injuries, fractures (Kirk et al 2005) (Schenck, Marchant-Forde 2018), infected skin lesions, foot lesions (Dewey 1993), and claw lesions (Heinonen et al 2006) have also been described. Osteomalacia and osteoporosis are more common in gilts and parity one sows, while older sows have been found to be more prone to foot problems (Schenck, Marchant-Forde 2018). Tinkle and colleagues evaluated overgrown claws that were trimmed to a length of 5.5 cm from the coronary band and saw significant improvement in gait in response to claw trimming. This improvement included a decrease in swing and stride duration, decreased breakover, and increased swing: stance ratio, and velocity (Tinkle et al 2017). Cador and colleagues found lameness to be positively correlated with heel lesions and dewclaw lesions (Cador et al 2014). A study of a Swedish swine herds investigated sows found dead or sows that were euthanized and identified arthritis in 36.4% of cases (Engblom et al 2008). Kirk and colleagues evaluated culled sows (spontaneously died or euthanized) that presented with locomotor disorders, in Danish pig herds, 265 pigs were necropsied. Seventy-two percent of the animals were euthanized due to locomotor issues including arthritis (24%) and fractures (16%). *Arcanobacterium pyogenes* was determined to be the main cause of arthritis (Kirk et al 2005). Further, a herd level investigation for veterinarians is difficult and may take months to get enough representative samples. Dewey and colleagues concluded that the combination of clinical examination and gross post mortem evaluation was a good method for diagnosing the cause of lameness in individual sows (Dewey 1993).

Environmental

This section will discuss housing, flooring, and feeding types and their effects on lameness in pigs. Schenck and Marchant-Forde found that group housed sows tend to have more injuries and stall housed sows tend to have more joint, foot and leg problems. They also reported shorter longevity and higher incidence of injury with individual, electronic sow feeders (three parities), compared to sows fed as a group in individual feeding stalls (3.9

parities) (Schenck, Marchant-Forde 2018). The authors looked at the lifespan differences in sows raised on two different flooring types: solid floor with straw, and slatted floor. Leg and locomotor problems were the most frequent reasons for culling (21.32% culled on solid floors and 16.27% culled on slated floors), but sows kept on solid flooring stayed in production longer. Sows culled due to leg problems remained in production for a longer period of time if managed on solid floors and the productive time of sows that were removed due to death was better on solid flooring (Soltesz 2012). Animals housed on slats had twice the odds of being lame and 3-7 times the odds of being severely lame when compared to animals housed on solid flooring (Heinonen et al 2006). KilBride and colleagues evaluated 98 herds raised on varying floor types and found an increased risk to abnormal gait in pregnant sows housed on slatted floors, compared to solid concrete floors with straw or on soil. Their analysis did not identify significant associations between flooring type and abnormal gait in gilts (KilBride et al 2009). Cador and colleagues also found concrete slated floors to be a risk factor when compared to straw (Cador et al 2014). Pluym and others found that claw lesions and lameness are more common in group housing systems, though did not find lameness or claw lesions to be significantly different pens with electronic sow feeders and free access stalls. (Pluym et al 2011). Cador and colleagues also reported leg problems occur more frequently in group-housing than in individual-housing systems. A logistic regression model was used to identify factors which significantly increased the risk of leg problems. These included housing in large groups, dirty floors, high levels of ammonia, severely restricted feeding during the last stage of pregnancy, and high sow to farm employee ratio (Cador et al 2014).

Genetic

A variety of genetic factors associated with lameness have been reported in the literature. A study by Jorgensen and Andersen evaluated the 1) the heritability and genetic correlations of OC in different joints and 2) genetic correlations between OC, leg weakness and production traits. The results from this study found Landrace boars were more severely affected with OC than Yorkshire boars at the humoral condyles, distal ulna growth line, femoral condyles, distal tibia and medial trochlear ridge of talus. There also appeared to be a genetic correlation between OC and leg weakness in the Yorkshire breed. Specifically, OC at the humeral condyles and the leg weakness traits of buck-kneed forelegs, forelegs turned out and stiffness in the front and rear. Further, in both the Landrace and Yorkshire, OC in femoral condyles showed a high correlation with hind legs turned out and a lower correlation with stiffness in the front (Jorgensen, Andersen 2000). Lundeheim evaluated OC in breeds and found Landrace to be the inferior breed for OC scores and leg weakness (Lundeheim, 1987). In contrast, Yorkshires had 2-7 times the odds of being lame when compared to Landrace or crossbred pigs in a study by Heinonen (Heinonen et al 2006). Lastly, Schenck and Marchant-Forde reported low levels of backfat to be associated with leg weakness problems (Schenck, Marchant-Forde 2018).

Management

Schenck and Marchant-Forde have reported that the cull rate for locomotor problems decreases as age increases. This is thought to be due to culling lame animals earlier in life. Some of the risk factors of higher concern with younger females include nutritional problems, poor conformation, management and the environment (Schenck, Marchant-Forde 2018). Further, a study by Bonde and colleagues looked at limb disorders, injuries, body condition and lying down behavior in commercial sows. The researchers found more sows displaying difficulty laying down (41% of 555) than were lame (15% of 570). Lesions noted by the researchers included skin wounds on the lateral hind feet or shoulders which were both observed in about 20% of the sows. They also found shoulder wounds were more common in thin or lame sows but fat sows were more likely to show stepping behavior when lying down. Additional observations included slipping, associated with hind feet lesions, and overgrown hooves associated with abnormal lying down behavior (Bonde et al 2004). There are multiple management factors to consider while working to prevent lameness cases as well as treat lameness cases.

Diagnosis

Diagnosing swine lameness is a challenge. In addition to the multifactorial nature of lameness as described in previous sections, there may be significant costs associated with the investigation and a significant amount of time may be required before a veterinarian is able to evaluate a sufficient number of affected animals. Rossow describes two diagnostic goals with lameness workups, 1) identify the causative agent and/or 2) provide negative results to rule out differentials (Rossow, 2010). Ultimately, our goal is to identify the treatable and manageable factors associated with a lameness case, so we can appropriately tend to animals that are currently affected as well as prevent these issues in the future. In a proceedings paper by Rossow, information about specimen collection including the number and type of animals to sample as well as sample handling prior to submission to the lab was described. Rossow also suggested that the pig and sample selection are the most important piece of a diagnostic work up. Clinical findings are also categorized in list format: gross joint lesions, swollen feet, swollen joints (with and without trauma), splay legs, osteochondrosis dissecans (OCD) and foot lesions and are discussed separately by age of pig and include differentials for the cause of each. The author describes the appearance of the clinical findings, followed by common differentials for each finding. (Rossow 2010). A second study focused more on diagnostic testing, discussed the use of histology to study hindlimb claws with deformities associated with overgrowth and change in gait. The claws were evaluated histologically to better understand an etiology for overgrowth. While the authors failed to identify prominent gross or histological findings they do not believe claw overgrowth represents primary laminitis in the pig. Overgrowth was defined as tow growth measuring >55 mm in length (Newman et al 2015).

This chapter discussed previous research completed on lameness detection and evaluation methods, lameness etiologies, and diagnosis of lameness. A significant amount of knowledge has been gained by these research efforts. Researchers, veterinarians and producers have and will continue to benefit from these findings. A review of sow lameness by Supakorn and colleagues in 2018 suggests research is still needed to accurately evaluate lameness lesions, examine nutrient requirements for optimum foot health, investigate genetic effects on feet and leg conformation, define the supplemental vitamins and/or mineral levels and duration for usage (Supakorn et al 2018). In addition, a consistent diagnostic approach to lameness cases in the field is has not been identified. The ability to detect lame animals, early in the disease is critical. It is also important that veterinarians and diagnosticians consider a comprehensive list of differentials that include infectious, management, nutritional, environmental, and genetic factors, among others. To appropriately rule in or out differentials it is important that the correct animals are sampled, and the correct samples are collected from those animals. What had not been identified in the literature was a tool that addresses all these components.

The Swine Lameness Diagnostic Manual developed by Karriker and colleagues incorporates 112 differentials into 5 decision trees, each representing a body system that may be affected in a case of lameness. The five body systems included: (1) central nervous, (2) peripheral nervous, (3) musculoskeletal, (4) integumentary, (5) digestive/metabolic. Following each physical examination, a veterinarian selected one of the five body systems or a combination of the five body systems as the most likely to be contributing to the case. The veterinarian used the decision tree for the selected system(s) to determine the lameness etiology. The decision trees included a series of yes or no questions that the veterinarian would answer based on the specific lameness case and would eventually end at a presumptive diagnosis. The decision trees also include sample collection instructions to help confirm or rule-out differentials (Karriker et al 2014). In comparison to studies mentioned previously, the value of the Manual’s design is its field-based application, and consideration of an extensive differential list, while helping veterinarian narrow down a list differentials. The manual will be discussed further in Chapter 4.

CHAPTER 3. VALIDATION OF STANDING AND LOCOMOTION LAMENESS SCORING, BEHAVIORAL ASSESSMENTS, AND MECHANICAL NOCICEPTIVE THRESHOLD TESTING ON NATURALLY OCCURRING SOW LAMENESS

Lameness is a major cause for premature sow culling in the swine industry (Anil et al., 2005). It has been estimated that 32% of sows culled for lameness have only produced one litter (Boyle et al., 1998). Lameness has been estimated to cost the United States swine industry approximately $23 million/year (Butters-Johnson et al, 2011). Continued research on tools that may assist veterinarians and farm employees in identifying and managing lame animals is an important step toward addressing these industry impacts. Several clinical lameness diagnostic tools have been successfully validated using a sow model of induced lameness. These tools include behavioral assessments, standing and walking lameness scoring, kinematics, and mechanical nociceptive threshold (MNT) tests (Karriker et al 2013, Mohling et al 2014a, Mohling et al 2014b). This work validated the tests on chemical models of lameness but they have not been validated on naturally occurring lameness in sows. The objectives of this study were to validate standing lameness scoring, locomotion lameness scoring and MNT testing on naturally occurring lameness in sows and gilts.

Animals and Location

All procedures were approved by the Iowa State University Institutional Animal Care and Use Committee (IACUC). A total of 55 crossbred gilts and sows ranging in parity from 0 to 7 were enrolled in the study (six groups over a three-month period). Gilts and sows were visually assessed for lameness on the commercial sow farm using a standing lameness score (Table 1) and/or the presence of gross lesions associated with one or multiple limbs. Animals were housed at the commercial farm in a mix of stalls and group housing. Flooring was fully slatted concrete. Animals were transported approximately 60-minutes from the farm to the

Swine Intensive Studies Laboratory (SISL) at Iowa State University Ames, IA and allowed to rest and acclimate to the environment for one day. After acclimation, all animals were re-evaluated by the veterinarian for the presence of lameness at SISL. To avoid confounding injury due to aggression, each animal was housed individually in the SISL in a concrete pen providing 5.1 m2 of space and a 0.6 m deep concrete ledge along the rear wall of the pen where the animals were fed. A rubber mat (FarmTek, Dyersville, IA) was provided for animal comfort. All animals were fed 2.2 kg of a commercial ground ration twice daily that was formulated to meet or exceed their dietary, non-gestating requirements according to Swine National Research Council (NRC) guidelines (2012). Animals had ad libitum access to water via one nipple drinker that was positioned over a grate. Pens were set up in two rows with a central aisle and allowed for nose to nose contact with cohorts. Lights were on a 12:12 light: dark cycle with light hours between 0600 and 1800. Caretakers observed all animals twice daily and verified they were able to rise and were ambulatory on all four limbs.

Standing and Locomotion Lameness Scoring

The standing lameness score was re-evaluated on the testing day in the animal's individual home pen (Table 1). Animals with more severe signs than those described in Table 1, such as non-weight bearing, were excluded from the study.

Table 1. Standing lameness score

Score	Description
0	Equal weight bearing on all 4 limbs and no toe tapping
1	Sow displayed any of the following: abnormal stance defined as slight arched back, lowered head, difficulty standing but was bearing weight on all four legs, the affected lame leg was bearing less weight, toe tapping

The locomotion lameness score was evaluated while the animal was walking from her individual home pen to the MNT testing stall. This score was determined based on the presence or absence of abnormalities associated with her gait (Table 2).

Table 2. Locomotion lameness score

Score	Description
0	Sow did not appear lame during walking
1	Sow presented stiff, ataxic, displayed a swaying gait, had a shortened stride, or had a visible limp. She had some difficulty with exercise or displayed a moderate kyphotic posture

Mechanical Nociceptive Threshold Test

The animals entered a modified gestation stall (0.61m x 2m) located outside of the animals' home pens. During the MNT tests, animals were offered a ground ration while held in the evaluation stall, in addition to the morning ration they were given in their home pen. The same technician performed all MNT tests on all animals during all test days. The technician applying the pressure algometer was blind to the numeric output values during the pain sensitivity test (mechanical nociceptive threshold) assessment, with the device positioned to keep output in view of a second technician that recorded these values. The MNT was evaluated on each animal using a hand-held Pressure Algometer (PA; Wagner Force Ten FDX 50 Compact Digital Force Gage; Wagner Instruments, Riverside, CT). The limb identified by the veterinarian to be lame and the opposite limb defined as non-lame, were evaluated. If the lameness could not be localized to a single limb, all four limbs were evaluated. Random selection of the right forelimb and right hind limb, or the left forelimb and the left hind limb was completed for PA testing on control animals. The PA had a 1 centimeter^2 flat rubber tip that was used to quantify MNT in kilograms of force (kgf). The

MNT was defined as the point a withdrawal response was seen. When an animal moved its leg away from the pressure, the PA was removed, and the kg of force value was recorded.

The application rate at which force was steadily increased for all animals on all landmarks was approximately 1 kilogram of additional force/second. The PA was held perpendicular to the limb and pressure was applied 1 centimeter above the coronary band on the lateral aspect of the lateral claw. Animals were first de-sensitized by the application of slight pressure with the evaluator's hands on the medial and lateral aspects of the limb from the hock or elbow, down to the location of the dew claw. This process was completed until the animal did not react to the presence of pressure two consecutive times. If there was no withdrawal the test was terminated at approximately 10 kg of force. The MNT test was repeated in triplicate on each limb selected for testing.

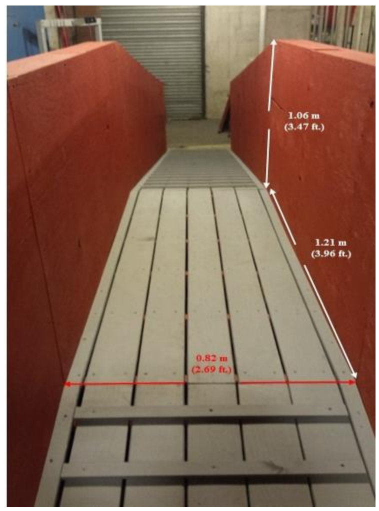
Obstacle Course

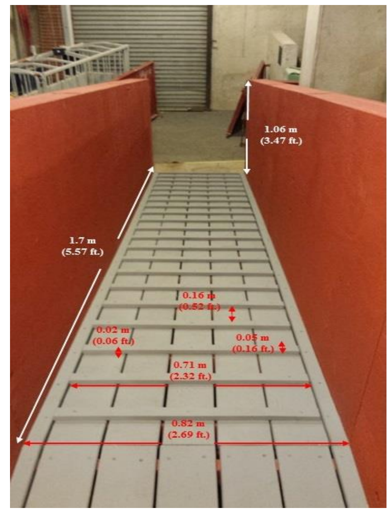
Following the PA measurements, the animal was removed from the stall and directed through the obstacle course (Figures 1a-1c, 2) by a designated handler. The obstacle course measured 45 m long × 1.5 m wide and included two obstacles. The two obstacles represented those commonly found on farms including a loading chute (ramp) and the step into and out of a farrowing crate (wooden boards).

Obstacle One (Ramp)

The ramp (Figure 1) was constructed of wood and had ascending (Figure 1a) and descending (Figure 1c) slopes set at 170.18 cm length x 82.55 cm internal width x 110.49 cm external width x 106.68 cm height. The internal width of the ramp was based on discussions with industry personnel about the width of a commercial sow from shoulder to shoulder. The ascending and descending slopes were at an 11° slope based on Transportation Quality

Assurance (TQA) recommendations. Connecting the ascending and descending ramp was a walkway (Figure 1b) set at 121.92 cm length x 82.55 cm width x 106.68 cm height. Twenty-one cleats measuring 71.12 cm length x 5.08 cm width x 2.54 cm height) were spaced at 16.51 cm intervals in both ascending and descending slopes (TQA, NPB).





(1a) (1b) (1c)

Figure 1. Obstacle Course Ramp (1a) Obstacle course ramp incline, (1b) Obstacle course walkway, (1c) Obstacle course ramp decline

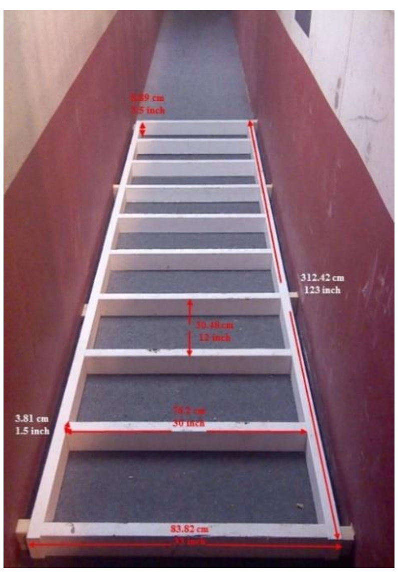


Figure 2. Obstacle course wooden boards

Obstacle Two (Wooden boards)

Ten wooden boards (Figure 2) that measured 8.89 cm height x 76.2 cm width x 3.81 cm depth were spaced 30.48 cm apart and were attached to a wooden frame. The wooden frame measured 312.42 cm length x 83.82 cm width x 8.89 cm height. These measurements were selected to require the sows to lift and flex their limbs while still being able to cross the obstacle.

Behavioral Observation

Five color cameras (Panasonic, Model WV-CP-484, Matsushita Co. LTD., Kadoma, Japan) were placed above the obstacles in the SISL (Figure 3). Three cameras were positioned over the ramp and two cameras were positioned over the wooden boards. Video was collected at a speed of 10 frames/second and saved to a computer hard disk using Handy AVI (HandiAvi version 4.3 D, Anderson's AZcendant Software, Tempe, AZ, USA). Following collection of all live animal data the video recordings were reviewed by a veterinary medicine student trained to score the animal-human interaction. The student was blinded to the lameness status of the sows (lame vs. non-lame). All video clips were reviewed by the same student. Behavioral outcomes included 1) time in seconds required to complete the obstacles (specific intervals are described in Table 3) and 2) animal-human interaction time which included contact with the person or an object operated by the person (ramp incline interventions, ramp walkway interventions, ramp decline interventions, total ramp obstacle interventions, and total ladder obstacle interventions).

Table 3. Time to complete obstacles

Measurement (seconds)	Description
Incline ramp	Started as the animal's shoulders cross onto the ramp and ended as the animal's hind crossed off the incline of the ramp
Walkway	Started as the animal's front feet and shoulders stepped onto the walkway and ended as the animal's hind crossed off the walkway
Decline ramp	Started as the animal's shoulders crossed onto the declining portion of the ramp and ended as the animal's hind crossed off the ramp
Traverse ramp	Started as the animal's shoulders crossed onto the incline portion of the ramp and ended as the animal's hind crossed off the decline portion of the ramp
Traverse wooden boards	Started as the animal's two front legs and shoulders positioned inside the wooden boards and ended as the two hind legs stepped off the wooden boards and contacted the handling course floor

Sow-Human Interaction

Handler interaction was used if the sow stopped forward movement for 10 continuous seconds at any point on the handling course. Each level of interaction that occurred between the sow and the handler was completed in 20 second intervals. Handler interaction had a defined order until the sow resumed forward movement: 1) Noise maker (plastic coffee can filled with metal pieces), 2) Sorting panel used to apply pressure to the animal's rear, 3) Handler used their hands to make contact with the sow's back, 4) Feed placed in front of the sow and, 5) Rattle paddle used to make contact with the animal's back (without striking the sow). After all interaction levels had been applied, she was left to rest for five minutes. In the event that the sow went down on two legs or laid down on the obstacle course she was left to rest for 10 minutes, without intervention. After a period of rest, animals were encouraged to continue moving through the course beginning with intervention number one. If the sow did not complete the obstacle course in 40 minutes, she was returned to her home pen and was recorded as a sow who did not complete the obstacle course due to time limitations.

Behavioral Training

A veterinary medicine student was trained to score the animal-human interaction from the video clips played at real time at the Iowa State University Animal Behavior Laboratory. Four, 30-minute video clips were selected using the Excel random number generator software; two video clips from the ramp and two video clips from the wooden boards. The trainer and the student scored the same four video clips until 90% inter-reliability was achieved. Inter-reliability was not successfully achieved on the first attempt, so the trainer and student reviewed the ethogram and example video clips to reiterate definitions of what to look for. Through the process, definitions were modified as needed to reliably evaluate the videos.

Assessment of Suspected Body System

A physical examination was performed by a veterinarian on each sow in their individual pen after completion of the obstacle course. The same veterinarian examined all sows enrolled in the study. The veterinarian also examined the sows on the commercial farm at enrollment into the study and was not blinded to the lameness score prior to physical examination in the SISL. The physical examination findings directed the veterinarian to one or more of five body systems suspected to be involved in the lameness: 1) central nervous system, 2) peripheral nervous system, 3) digestive/metabolic system, 4) musculoskeletal system, 5) integumentary system.

Data Analysis

Each sow was considered an experimental unit. Time (to move over the ramp and wooden boards) and human-sow intervention (five levels of intervention) were shown to be highly correlated and were therefore analyzed separately using generalized linear mixed model methods (PROC GLIMMIX; SAS v9.4, SAS Inst. Inc., Cary, NC). Ramp incline time, ramp walkway time, ramp decline time, total ramp obstacle time and total ladder obstacle time were transformed to log scale using the Gamma distribution option of the model statement. Five models were developed for human-sow intervention: ramp incline interventions, ramp walkway interventions, ramp decline interventions, total ramp obstacle interventions, and total ladder obstacle interventions and were transformed to log scale using the Poisson distribution option of the model statement. Fixed effects of group (n=6), parity (0-7), suspected lameness system (none (8) integumentary (20), musculoskeletal (15), both integumentary and musculoskeletal (12)) standing lameness score (0,1), and walking lameness score (0,1) were used for all models. Sow body weight (kg) was fit as a linear covariate. For the MNT model, the statistical design was a complete randomized design using a generalized linear mixed model (PROC Glimmix) with the model including the fixed effects of sow BW (kg), suspected lameness system and the leg suspected to be lame (right hind or left hind). Statistical differences were reported when individual model main effects were a significant source of variation ($P \leq 0.05$). Further, when individual model main effects were a significant source of variation, main effect levels were separated using the PDIFF option which returns the P values for least squares means differences between different levels within each level of fixed class effects. Results for fixed effects are reported as least squares means ± SE (LSMeans ± SE) after being back transformed from the log scale using the ILINK option in the LSMEANS statement. Results for covariates are reported as regression coefficients ± SE.

Results

There were no lameness cases suspected to be associated with the central nervous system, the peripheral nervous system or the digestive/metabolic system, based on the veterinary evaluation.

Mechanical Nociceptive Threshold

Data analysis for MNT was conducted only on the hind limbs because there was not a statistically significant number of lameness cases to analyze associated with the forelimbs. Lameness etiology was not a source of variation when assessing MNT on the right ($P = 0.55$) and left ($P = 0.36$) hind limbs. There were differences in the MNT scores when comparing a left ($P = 0.02$) hind limb lameness or right hind limb ($P = 0.06$) lameness to non-lame hind limbs.

Obstacle Course

Lameness etiology was a significant source of variation when comparing time to walk over the walkway ($P=0.03$) as well as time to traverse the total ramp ($P=0.02$) with control animals being the slowest (Table 4). The data suggested that lameness etiology was only a source of variation when comparing time to traverse total ramp ($P = 0.02$) where control and musculoskeletal were slower.

Table 4. Time (seconds) needed to traverse ramp and wooden boards by system affected

	Suspect systems				
Measure	Control	Integumentary	Musculoskeletal	Integumentary/ musculoskeletal	**P-value**
Incline ramp	35.4±12.6	20.4±3.6	42±10.8	27±7.2	0.11
Walkway	117±61.8^{a}	20.4±6^{b}	20.4±8.4^{b}	14.4±6^{b}	0.03
Decline ramp	109.2±31.2	85.2±12.26	145.2±30.6	88.2±18.6	0.27

Table 4. continued

	Suspect system				
Measure	Control	Integumentary	Musculoskeletal	Integumentary/ musculoskeletal	**P-value**
Traverse ramp	247.2±66[a,c]	124.2±17.4[b]	234.6±45.6[a]	122.4±23.4[b,c]	0.02
Traverse wooden boards	56.4±15.6	35.4±4.2	35.4±6.6	40.2±8.4	0.43

*values with matching superscripts are not significantly different

Lameness etiology was a source of variation when comparing the number of human interventions needed during incline ramp (P=0.0001) with musculoskeletal requiring the most interactions and integumentary requiring the least. The walkway revealed the etiology to be a source of variation with control animals requiring the most interactions through that part of the ramp (P=0.003). Musculoskeletal animals needed the most on the decline ramp (P=0.004; Table 5).

Table 5. Animal-human interactions (count) needed to traverse ramp regarding suspect systems

	Suspect systems				**P-value**
Measure	Control	Integumentary	Musculoskeletal	Integumentary/ musculoskeletal	
Incline ramp	13.11±1.80[a]	6.84±0.69[b]	20.89±2.23[c]	9.11±1.02[a]	0.0001
Walkway	4.07±1.26[a]	1.44±0.34[b,c]	2.10±0.51[a,c]	1.52±0.40[b,c]	0.05
Decline ramp	6.53±1.11[a]	4.76±0.54[a]	11.14±1.41	7.02±0.93[a]	0.004

*values with matching superscripts are not significantly different

Standing and locomotion lameness scores were not confirmed as explanations of variation in the number of human interactions required during any of the obstacle parameters (Incline ramp, Walkway, Decline ramp, Traverse ramp and Wooden boards. This is most likely a reflection of sample size once the study population is subdivided into 4 categories and because standing lame and locomotion scores would be expected to have high correlation. There were trends of interest and these are presented in Table 6 in support of further study.

Table 6. Average number of animal-human interactions needed to traverse ramp and wooden boards based on standing and locomotion lameness scores

Measure (n)	**Standing lameness score**		**Locomotion lameness score**	
	Lame	Non-lame	Lame	Non-lame
Incline ramp	1.95	1.09	1.22	1.56
Walkway	3.62	2.98	2.83	3.66
Decline ramp	8.89	7.87	9.34	7.35
Traverse ramp	14.04	12.14	13.35	12.64
Wooden boards	1.76	2.39	1.57	2.58

Standing lameness score was a significant source of variation (P=0.008) when comparing time to incline ramp with non-lame animals taking longer (Table 7). Locomotion lameness score was a significant source of variation for incline ramp (P=0.006) with lame animals taking longer and walkway with lame animals taking longer (P=0.003; Table 7). Locomotion lameness score was also a source of variation when time to traverse the entire ramp (P=0.02) and time to traverse the wooden boards (P=0.008) with lame animals taking longer in both cases.

Table 7. Time (seconds) needed to traverse ramp and wooden boards based on standing and locomotion lameness scores

Measure	Standing lameness score		P-value	Locomotion lameness score		P-value
	Lame	Non-lame		Lame	Non-lame	
Incline ramp	19.8±3.0	45±8.4	0.008	53.4±10.2	16.8±3.0	0.006
Walkway	22.8±5.4	39.6±12.6	0.24	69.6±23.4	12.6±3.6	0.003
Decline ramp	70.2±13.2	106.2±15.6	0.87	114±18	95.4±14.4	0.50
Traverse ramp	155.4±19.2	191.4±27	0.32	233.4±36	127.2±18	0.02
Traverse wooden boards	40.8±4.8	41.4±5.4	0.95	57±8.4	29.4±4.2	0.008

Discussion

The results from this study support the paradigm that lame animals on a farm may take more time and require more intervention by their handlers to move throughout their environment when compared to non-lame sows. However, there were several examples where non-lame sows took longer and required more interactions from handlers such as when they were entering the ramp incline or spending time on the walkway. Based on researcher observations, some non-lame sows spent more time investigating their environment than lame sows and further research into this effect is warranted. These findings oppose the hypothesized results that lame animals would uniformly require more time and intervention to move through obstacles in their path in all situations. Possible explanations may include: 1) the pain associated with locomotion for lame animals may cause more focus on the path in front of them and less distraction by the environment around them, 2) the lame sows may have reacted quicker to handler interventions due to a heightened sensitivity from pain, and lastly 3) once removed from their individual pen, lame sows may have been more motivated to return to their individual pens where they were previously not being asked to move. A future research consideration may include performing behavioral observations in the animals' original farm environment where novel stimuli to explore is less likely to be encountered. While the laboratory obstacles were designed to simulate common obstacles found on farms, there are many environmental factors that could not be replicated. These factors include noises such as those from other animals and farm equipment, as well as smells, and sights, that may influence the speed an animal travels from point A to B. A better understanding of the impact of these would improve our understanding about the affect the animals' environment has on the time and interventions required to move lame and non-lame animals.

The results from this study confirmed the ability of MNT to detect lameness but highlighted limitations with the use of MNT testing to discriminate between lameness etiologies. There were two factors that may have influenced the results of the animals' nociceptive threshold. First, the pressure was applied by the PA at a focal and consistent location on the limbs of all animals. The withdrawal response by the animal may have been influenced by the location of the issue causing the lameness. For example, we would expect variation in response to pressure applied near the coronary band on an animal with osteochondrosis at the stifle, compared to an animal with an injury on the distal limb. The location of the injury may also influence the animals' desire to withdraw the affected limb, arbitrarily heightening the kilograms of force tolerated by the animal. Second, the withdrawal response on the sound limb may have also been influenced by the animals' resistance to put weight on the affected limb. A future research consideration may include testing the utility of mechanical threshold testing in field settings and evaluating the level of agreement when used by different farm employees on sows with known lameness etiologies. Lastly, the behavior assessments, MNT testing and walking and standing lameness scoring were less correlative when evaluating the body system suspected to influence lameness. The multifactorial nature of lameness makes the determination of contributing body systems difficult. Ultimately the suspected system would remain a suspect until some level of diagnostic confirmation is completed.

Readers should note that the results from this study may not appropriately predict the time and interaction needed to move gilts and sows with more severe lameness.

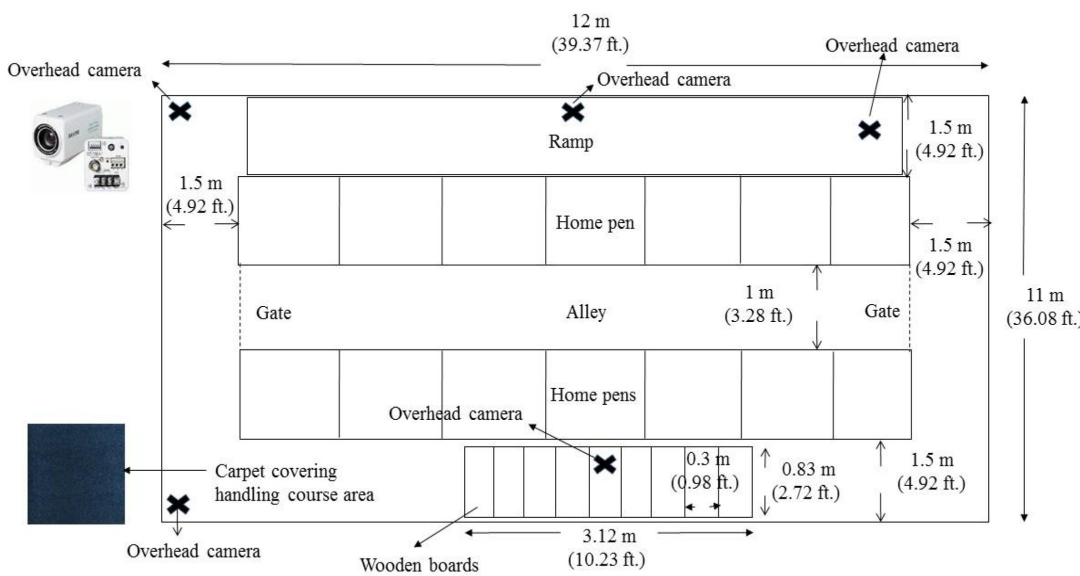


Figure 3. Obstacle course and camera placement

CHAPTER 4. VALIDATION OF THE SWINE LAMENESS DIAGNOSTIC MANUAL ON NATURALLY OCCURRING SOW LAMENESS

Second to reproductive problems lameness is a major cause for premature sow culling in the swine industry (Anil et al., 2005). It has been estimated that 32% of sows culled for lameness have only produced one litter (Boyle et al., 1998). Lameness has been estimated to cost the United States swine industry approximately $23 million/year (Butters-Johnson et al, 2011). There have been many factors identified that contribute to lameness in a population of sows as described in chapter 2. Further, due to the multifactorial nature of many lameness cases, an accurate diagnosis of the underlying cause of lameness is challenging for veterinarians in the field. In response to industry interest in a consistent diagnostic approach to lameness cases in the field, Karriker and colleagues (2014) created the Swine Lameness Diagnostic Manual to help guide veterinarians to a presumptive diagnosis for lameness cases observed within a herd. Many resources were used during the development of the Manual including Diseases of Swine 10th edition, the Merck Veterinary Manual, scientific literature review, analysis of proceedings and case studies, field experiences, and expertise from swine veterinarians and swine diagnosticians. The Manual is organized in three sections. The first section includes five decision trees, each representing a body system that may be affected in a lameness case: 1) central nervous system, 2) peripheral nervous system, 3) digestive/metabolic system, 4) musculoskeletal system, and 5) integumentary system. Each decision tree comprises a comprehensive list of differentials that are most appropriate to the individual system. Throughout the five decision trees, there is a combined total of 112 differentials listed in the Swine Lameness Diagnostic Manual. The veterinarian is first directed to select the body system or systems they expect to be affected. The system(s) selected by the veterinarian determine the decision trees he or she will use. Based on further clinical observations the veterinarian is to work through the decision trees, answering yes or no questions until arriving at a differential or list of possible differentials. The decision trees also include sample collection techniques. These techniques are described in detail in the second section of the Manual. Details covered include sample size recommendations, landmarks to use to access specific samples and extraction technique how-to guides for more difficult sample retrieval. The third section of the manual is a gallery of example lesion images for veterinarian reference. The objective of this study was to test the utility of the Swine Lameness Diagnostic Manual on natural lameness cases in sows and gilts.

Animals and Location

A total of 60 crossbred gilts and sows ranging in parity from 0 to 8 were enrolled in the case-control study. Animal care and husbandry protocols for this experiment were overseen by the primary investigator. All procedures were approved by the Iowa State University Institutional Animal Care and Use Committee (IACUC). The animals were visually assessed for lameness on the commercial farm using a standing lameness score (Table 1) and/or the presence of gross lesions associated with one or multiple limbs. The animals were transported from the farm to the Swine Intensive Studies Laboratory (SISL) at Iowa State University (Ames, IA) and allowed to rest and acclimate to the environment for one day. To avoid confounding injury due to aggression, each animal was housed individually. Each animal was housed in a concrete pen providing 5.1 meters^2 of space and a 0.6 meter deep concrete ledge along the rear wall of the pen where the animals were fed. A rubber mat (FarmTek, Dyersville, IA) was provided for animal comfort. All animals were fed 2.2 kilograms (kg) of a commercial ground ration twice daily that was formulated to meet their dietary requirements. Animals had ad libitum access to water via one nipple drinker that was positioned over a grate. Pens were set up in two rows with a central aisle and allowed for nose to nose contact with cohorts. Lights were on a 12:12 light: dark cycle with light hours between 0600 and 1800. Caretakers observed all animals twice daily and verified they were able to rise and were ambulatory on all four limbs. A veterinarian specializing in swine medicine selected two to three animals for assessment each day, prioritizing animals that were displaying lameness that appeared to be progressing in severity. The standing lameness score was re-evaluated on testing day in the animal's individual home pen (Table 1).

Lameness Diagnostic Manual Application

A physical examination was performed by a veterinarian on each sow in their individual pen. The same veterinarian examined all sows enrolled in the study. The veterinarian also examined the sows on the commercial farm at enrollment into the study and was not blinded to the lameness score prior to physical examination in the SISL. The physical examination findings directed the veterinarian to one or more of five body systems: 1) central nervous system, 2) peripheral nervous system, 3) digestive/metabolic system, 4) musculoskeletal system, 5) integumentary system. For each of the five body systems, the Swine Lameness Diagnostic Manual included a decision tree comprised of a comprehensive list of differentials that are most appropriate to the individual system. The system(s) selected by the veterinarian following the initial examination, determined the decision tree(s) used. Based on further clinical observations, the veterinarian worked through the decision trees, answering questions until arriving at a differential or list of possible differentials. In addition to differentials, the decision trees included recommended antemortem and/or post mortem samples to collect as well as instructions for various sample collection techniques. After evaluation and collection of ante mortem samples, the animal was snared and euthanized using Pentobarbital Sodium (Fatal-Plus, Vortech Pharmaceuticals, Ltd), administered intravenously by accessing the auricular vasculature. A tourniquet was used at the base of the ear to improve visualization of the auricular vasculature. Chlorhexidine and alcohol were applied to the pinna of the ear to further improve visualization and to clean the surface of the ear prior to catheterization. A range of catheter styles were used during the study, but the authors recommend the use of a straight catheter or butterfly catheter, 20 to 22 gauge, with a max length of one inch, be used for mature sows and gilts. Following catheterization, a transparent film dressing (Tegaderm, 3M, St. Paul, MN) was applied to the catheter site to secure catheter placement. Heparinized saline was used to flush the catheter prior to administration of the euthanasia solution. The euthanasia solution was administered after connecting the syringe to the catheter with extension tubing. This improved safety for research personnel when a sow would move during administration. The euthanasia solution was administered to effect, at about 100mg/kg. Following euthanasia, postmortem sample collection was completed as recommended by the decision tree(s) and samples were submitted to the Iowa State University Veterinary Diagnostic Laboratory (Ames, IA). A summary of samples collected as well as tests completed is described in the results section.

Lameness Diagnostic Manual Evaluation

The accuracy of the diagnoses made by the Swine Lameness Diagnostic Manual were evaluated on a case-by-case basis by a panel of three swine veterinarians with swine medicine experience. The veterinarians were asked to assess the accuracy and completeness of each presumptive diagnosis given by the manual. Over a two-day period, the veterinarians reviewed ante mortem and postmortem data from 47 cases. Case information was presented by the same veterinarian who examined the animals throughout the study. The information was presented using Microsoft PowerPoint and included a written description of the animal's physical examination findings, the lameness manual's presumptive diagnosis, standing lameness score, locomotion lameness score, and a written description of the postmortem necropsy findings. Case information presented in a paper format included diagnostic lab reports and definitions of etiologies found within the Swine Lameness Diagnostic Manual. Additional information provided included the animals' parity (verbally reported) and photographs of gross necropsy findings (Sharp LC-65D64U Aquos 65" LCD). Using this information, the evaluators were asked to assess the accuracy and completeness of each presumptive diagnosis given by the manual and were to categorize the manual's diagnoses as 1) accurate and complete, 2) accurate and incomplete, or 3) inaccurate. An accurate and complete diagnosis was determined to be a diagnosis that was the most likely cause of the lameness based on the information provided. An accurate and incomplete diagnosis was determined to be a diagnosis that may have contributed to the lameness but was not likely the only etiology involved in the case. An inaccurate diagnosis was determined to be an unlikely etiology based on the information provided. The veterinarians were not limited on the amount of time that could be spent on an individual case. Clarification questions asked by a panel member were answered in front of all three veterinarians. The veterinarians recorded their written answers individually.

Results

There were no lameness cases suspected to be associated with the central nervous system, the peripheral nervous system or the digestive/metabolic system.

Lameness Diagnostic Manual

Following the physical examination, 47 sows and gilts were categorized into the following systems based on the system suspected to be contributing to the lameness: Integumentary (n=20), Musculoskeletal (n=15), Integumentary and musculoskeletal (n=12). The diagnoses given by the manual are summarized in Table 8.

Table 8. Differentials Suggested by the Swine Lameness Diagnostic Manual

15 cases (32%)	abscess associated with *Burkholderia pseudomallei*, *Corynebacterium* species, *Truperella pyogenes*, pressure sores, *E. Coli*, *Beta strep*, and *Staphylococcus*
13 cases (28%)	osteoarthritis, osteomalacia, osteochondrosis, osteochondrosis dissecans, neoplasia-lymphosarcoma, post-lactational osteodystrophy, apophysiolysis, epiphysiolysis, osteomyelitis, and proliferative osteitis, abrasion, bruising, bursitis, strain, sprain, myositis/cellulitis, *Chlostridium chauvoei*, *novyi*, *septicum*, and *perfringens*
11 cases (23%)	Flooring and conformation
4 cases (9%)	Vesicular diseases such as Foot-and-Mouth disease, San Miguel Sea Lion Virus, Swine Vesicular Disease, Vesicular Exanthema, Vesicular Stomatitis, Seneca Valley Virus
3 cases (6%)	epaxial muscle necrosis, and asymmetrical hindquarter syndrome, traumatic arthritis and soft tissue infection
2 cases (4%)	trauma from pen mates or unmaintained equipment, joint hemorrhage, and periarticular edema caused by Porcine Reproductive and Respiratory Syndrome (PRRSv), septic arthritis caused by *Haemophilus parasuis, Streptococcus suis, Erysipelothrix rhusiopathiae*, *Mycoplasma hyosynoviae, Mycoplasma hyorhinis, Staphylococcus* species, *Streptococcus equisimilis, E. Coli, Actinobacillus suis, Truperella*, *Brucella*, *Salmonella*, *Arcanobacterium*, or *Strep pyogenes*
1 case (2%)	Selenium toxicity and trauma

The veterinarians evaluating the accuracy of the Swine Lameness Diagnostic Manual reviewed all 47 lameness cases. In two of the 47 cases (4.3%) all three veterinarians found that the manual diagnosed the etiology accurately and completely. In four of the 47 cases (8.5%) at least two of the three veterinarians found that the manual diagnosed the etiology accurately and completely. In 29 of the 47 cases (61.1%) at least two of the three veterinarians found the diagnosis to be accurate but incomplete. In 17 of the 47 cases (36.2%) at least one veterinarian found the diagnosis to be inaccurate. Of the total responses, 18.1% were categorized as accurate and complete, 64.5% were categorized as accurate and incomplete, and 17.4% were categorized as incomplete.

Diagnostic Laboratory Submissions

The Swine Lameness Diagnostic Manual directed the veterinarian to collect specific diagnostic samples and submit samples for specific testing at the laboratory. Samples were submitted to the Iowa State University Veterinary Diagnostic Laboratory (Ames, IA). Sample collection was not recommended for every differential listed in the Swine Lameness Diagnostic Manual. Samples were submitted from 26 of the 60 sows and gilts evaluated during this study. Of the 26 diagnostic submissions, culture was completed on 81% (21/26) of the diagnostic submissions, histology was completed on 38% (10/26) of case submissions, molecular testing was completed on 23% (6/26) of the submissions, and toxicology was selected for one case. Diagnostic findings from are summarized in Table 9.

Table 9. Diagnostic Results from Laboratory Submissions

13 cases (50%)	*Staphylococcus* species
8 cases (31%)	*Trueperella pyogenes, Streptococcus* species
5 cases (19%)	dermatitis
2 cases (8%)	synovitis, Seneca Virus A
1 case (4%)	osteochondrosis, hematoma, fibrous connective tissue, bacterial infection with degeneration and necrosis, *Escherichia coli*, *Corynebacterium*, *Aerococcus*

Of the 26 cases that included diagnostic submissions, 69% (18/26) were from animals that were score one standing lame (Table 1), and 77% (20/26) were from animals that were score one lame while walking (Table 2).

Gross Lesion Summary

In addition to diagnostic sample submission, gross observations were recorded during the post mortem evaluations.

Animals that were score one standing lame and score one locomotion lame

Gross findings included observations made on any limb of the animal: cartilage irregularity associated with joint, pressure sore, abscess, joint mouse/osteochondrosis dissecans (OCD), gross swelling, hyperemic area of bone, hyperemic membrane associated with joint, sole ulcer, sole cracks, ruptured vesicle, hematoma, hoof wall crack, edematous subcutaneous tissue, bruising, hemorrhages on hoof, open sores on/around hoof, distal limb masses with defined encapsulated tunnels, superficial lesion, increase in synovial fluid, prominent and increased number of fimbriae in joint, hyperemic synovium, pocket of necrotic tissue with pieces of hard, spiculated, free bone and tissue that was dark brown in color.

Animals that were score one standing lame and score zero locomotion lame

Gross findings included observations made on any limb of the animal: cartilage irregularity, hyperemic synovium, superficial abscesses, OCD (osseous and cartilage consistency), wall cracks that appeared healed.

Animals that were score zero standing lame and score one locomotion lame

Gross findings included observations made on any limb of the animal: suspect pressure ulcer, cartilage irregularity, hyperemic synovium, abscess, joint mouse, bruising, proliferative synovium associated with joint.

Animals that were score zero standing lame and locomotion lame

Gross findings included observations made on any limb of the animal: bruising, gross swelling, cartilage irregularity, hyperemia at joint, hematoma, clear fluid pocket, suspected osseous structure in the subcutaneous tissue near the hock, skin lesion, decreased ossification on cross section evaluation of toe, bone thickening (dewclaw), subcutaneous hemorrhage, joint mouse, inflamed synovium.

Discussion

The results from the Swine Lameness Diagnostic Manual case review do not suggest it is an effective tool at diagnosing lameness etiologies. Given the wide variety of lesions as well as the case-specific and multifactorial nature of lameness, it is unlikely that the current manual could be improved to accurately diagnose most lameness cases. The “yes or no” question design of the decision trees is thought to have ruled-out differentials prematurely. However, the decision trees were designed to help veterinarians rule out differentials that could be evaluated based on history, observation, or gross observation before submitting samples for diagnostic testing. Differentials were categorized within a decision tree according to the effort and expense it may take to rule them out and ultimately considered a) causes that could be ruled out by direct observation or history, b) causes that could be ruled out by gross or microscopic lesions, or b) causes that require specific diagnostic testing. It can be assumed that once a veterinarian has collected samples, there are many differentials that have been ruled out which is valuable information, especially if diagnostic results are not definitive. For the purposes of this study, all 60 sows received an antemortem and post mortem evaluation.

The summary of the diagnostics submitted from the animals in this study highlight the diagnostic modalities that are commonly recommended when lameness cases are suspected to involve the musculoskeletal or integumentary systems: histology, bacteriology and molecular testing (Polymerase Chain Reaction). The results also highlight the more common diagnoses which should be interpreted carefully because they were not always associated with lameness. Lastly, lame and non-lame animals were evaluated for gross lesions. The summary above discusses many consistent findings in lame and non-lame animals. It is difficult to interpret the significance of a lesion in a lame animal if the same lesion has been identified in a non-lame animal. The authors describe a resource developed to help practitioners interpret observations associated with the feet of sows and gilts in Chapter five.

A strength of this study design included the ability to compare findings from lame animals and non-lame animals. Specifically, gross lesions identified at necropsy. These observations led to the development of the tool described in Chapter five. It is important that veterinarians become familiar with lesions that are observed in lame and non-lame animals and gauge their significance only in combination with behavioral observations and/or clinical history. A weakness of this study design includes the inability to evaluate the animals over a period of time. There are many etiologies previously discussed in this thesis that can contribute to lameness such as nutritional, conformation and environmental issues that are difficult to evaluate the true impact on an individual animal at one time point.

Successful treatment and management of lameness at the individual or herd level is dependent on the accuracy of the diagnosis. The results from this study have shown diagnostic accuracy to be difficult to achieve due to the multifactorial nature of lameness cases and the limitations of assessing an animal or a group of animals at one time point.

CHAPTER 5. VARIATIONS OF NORMAL: A LOOK AT NON-LAME SOWS' FEET

Lameness has been estimated to cost the United States swine industry approximately $23 million/year (Butters-Johnson et al, 2011). Treatment plans for lameness, including the use of pain mitigation drugs, judicious use of antibiotics and/or providing timely euthanasia, are critical for proper management of lame animals. Ultimately, treatment and management decisions are most effective when selected after a thorough evaluation has been completed. This approach should include a systematic evaluation of all body systems known to contribute to locomotor issues. As described in chapter four, these systems include: the central nervous system, peripheral nervous system, integumentary system, digestive/metabolic system and musculoskeletal system. The study described in chapter four allowed for ante mortem and post mortem examination of the distal limb of sows. As part of the post mortem examination, the authors collected images of the dorsal and palmar aspects of the feet.

Previous research has described readily observable foot lesions as “low hanging fruit” for diagnosis and treatment of sow lameness (Knauer et al 2007). What previous studies lacked was ante mortem assessment of the sows' lameness status prior to observing foot abnormalities on the slaughter line. As a result, every abnormality was interpreted to be a contributing part of the problem. Observations made during the study described in chapter four challenge this paradigm. During the post mortem evaluations there appeared to be consistent variations from what many may perceive to be a “normal sow foot” on the non-lame limbs. The authors recognized the opportunity to document these findings and provide veterinarians access to these images for reference during lameness workups. Similarly, in a study completed by Dewey and colleagues, researchers found the same lesions in animals culled due to lameness and animals culled for other reasons. Findings from animals culled for lameness included osteochondrosis (OC), arthrosis, infectious arthritis and foot problems. From animals culled for other reasons, researchers found arthrosis, foot lesions, and OC. The authors of this study went on to note that gross postmortem lesions of OC can be found in sows that are clinically non-lame and recommended interpreting the gross findings after other causes of lameness are ruled out and only when the findings are associated with a clinically affected leg (Dewey et al 1993).

This web-based resource is an empirical, descriptive review, highlighting variations of the sole, heal, toe, white line, and dew claws from non-lame limbs of commercial sows. The objective of this resource is to familiarize veterinarians and farm employees with the variations of foot appearance that can occur on non-lame sows but might be mistaken for true pathology. Individuals working through lameness cases may improve diagnostic accuracy and proper treatment of lameness cases if they look beyond the changes documented in the image library and look further for the cause of lameness.

Definition of Non-lame

A sow was considered non-lame while standing if she was bearing weight equally on all four limbs and she was not toe tapping (Table 1). Further, a sow was considered non-lame while walking if her gait was absent of stiffness, ataxia and swaying, there was no shortness of stride or visible limp and she did not display a kyphotic posture (Table 2).

Collection of Images

Following euthanasia, the dorsal and palmar/plantar aspects of the sows' feet were photographed. Images from known non-lame limbs were selected based on how well they represented one of the following six categories: heel, dew claw, hoof wall, sole, white-line, toe (length) (Figure 4; Breuer, Forseth, 2019).

Lameness Evaluation

A consistent physical evaluation will better assure identification and diagnosis of the underlying issue. During development of the Swine Lameness Diagnostic Manual, the authors identified 112 differentials for locomotor issues across 5 body systems. For this reason, it is important that a systematic evaluation is completed by veterinarians working-up lameness cases.

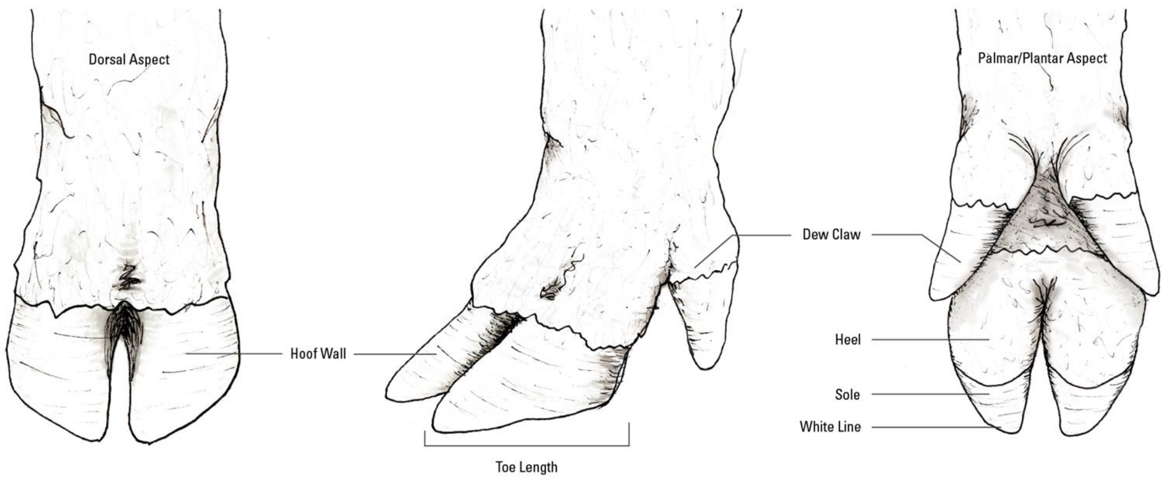


Figure 4. Anatomic landmarks of porcine foot

Anatomy

A second objective of this tool is to help establish consistency in the anatomic references and terminology associated with the pig foot. The ability to communicate accurately about what is seen in the field is critical for both veterinarians and diagnosticians.

The design of the foot varies significantly between species (Fick 2014). In the pig, the foot is defined as the limb below the fetlock joint and includes four digits. From the aspect lateral to the medial aspect, pig digits are numbered: five, four, three, two. The second and fifth are digits are the dewclaws (Figures 4,10). The third and fourth digits are weight bearing in the pig. In the sow, the dewclaws can bear weight on soft surfaces. The anatomy of all four digits includes the proximal phalange (P_1), middle phalange (P_2), and distal phalange (P_3), as well as 3 sesamoid bones. The heel is defined as the bulbar, posterior section on the ground surface of the foot (Figures 4 and 5). The hoof wall (Figures 4 and 6) is made up of a highly keratinized epidermis which allows for protection of underlying structures. The proximal portion of the hoof wall is defined by the coronary band. The sole is the anterior section of the ground surface of the hoof (Figures 4 and 8). Together, the sole and the heel make up the weight bearing portion of the sow's foot (Fick 2014). The white line connects the sole to the hoof wall (Van Amstel 2010). The white line is located from the heel on the abaxial (away from center) side of the claw around the tip of the toe and about 1/3 of the way back on the axial (center) side of the claw's weight bearing surface (Van Amstel 2010) (Figures 4,9). The toe, as defined by the hoof wall (Figures 4 and 6), includes the distal phalanx (P_3), the distal portion of the middle phalanx (P_2), the distal sesamoid bone and flexor and extensor tendons (Fick 2014). In mature sows the normal toe length is 45-50mm. In sows, the rate of growth usually exceeds the rate of wear (Figure 7) (Van Amstel 2010).

Figure 5. Heel

Figure 6. Hoof wall

Figure 7. Toe length

Figure 8. Sole

Figure 9. White line

Figure 10. Dewclaws

Image Library

The image library is an interactive, online-based resource that allows viewers to review six anatomical locations of sows' feet that highlight the variations observed during post mortem examination of commercial sows and gilts. Figure 11 displays a section of the library highlighting variations in heels of sows.

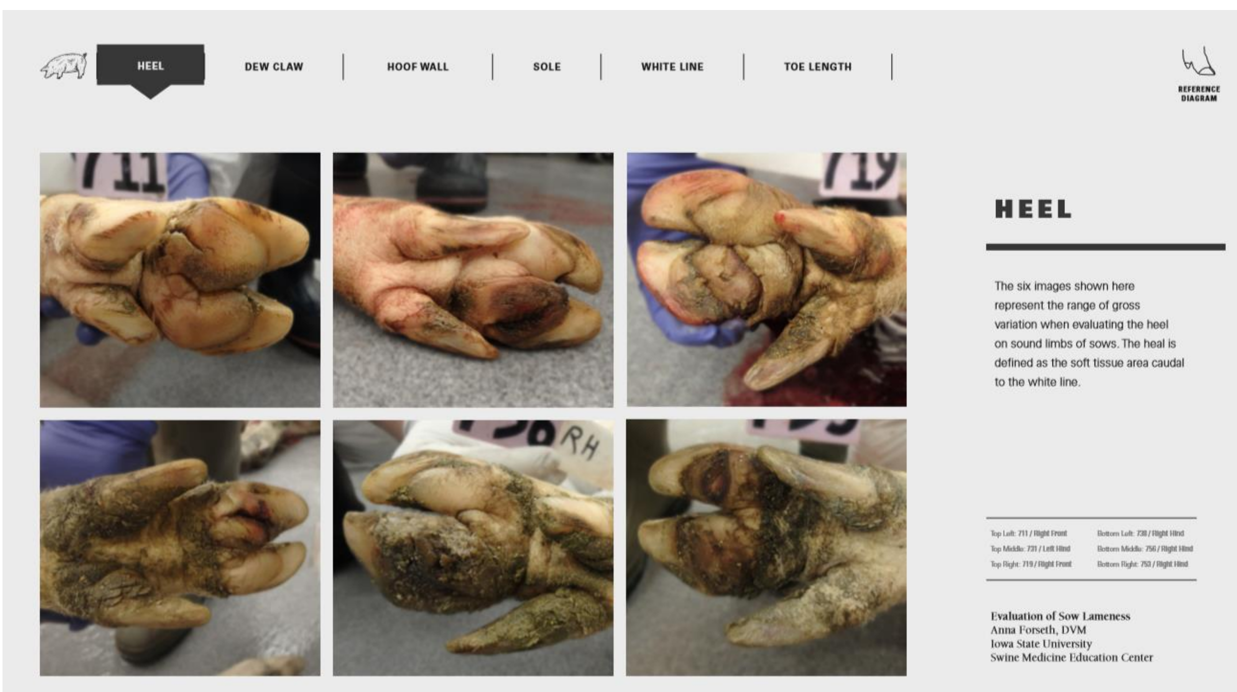


Figure 11. Image Library-Heel variations

Practical Application

Successful treatment and management of lameness cases is dependent on diagnostic accuracy. Through exposure to these variations of the sole, heal, toe, white line, and dew claws from non-lame limbs of commercial sows, veterinarians and producers working through lameness cases may improve diagnostic accuracy and proper treatment of lameness cases if they look beyond the changes documented in the image library from non-lame sows and look further for the cause of lameness. Veterinarians and producers should utilize this information while assessing distal limbs during routine examinations and lameness workups in the field. For a thorough evaluation, the authors recommend cleaning off the sows' feet using water under pressure from a hose, wearing a headlamp or using a flashlight and evaluate the sow while in a lateral position if possible to fully visualize the palmar and plantar aspects of the feet.

Discussion

The image library highlights variations on the feet of non-lame limbs that may otherwise be assumed to be a cause of lameness. The authors of this thesis see this resource as an opportunity to educate veterinarians though recognize that there are limitations associated with its use. The findings highlighted in these images are variations observable without any understanding of the condition of the deeper tissues. Asking viewers to make a comparison between these images and field observations without considering internal structures and the effect these more superficial findings may have on them, is a weakness of this tool. Secondly, this tool has not gone through a validation process. To validate this tool, objective study inclusion criteria would need to first be defined for each of the categories. This will help assure that the sows evaluated, display consistent types of variations. Live sows would be evaluated using these measurements so the observer could verify the animal was not lame. Additional details to consider would be the housing type, flooring type and feeding system used.

CHAPTER 6. CONCLUSION

Sow lameness is a production disease affecting not only animal welfare but also swine profitability. Second to reproductive problems, lameness is a major cause for premature sow culling in the swine industry (Anil et al., 2005). It has been estimated that 32% of sows culled for lameness have only produced one litter (Boyle et al., 1998). Lameness has been estimated to cost the United States swine industry approximately $23 million/year (Butters-Johnson et al, 2011). The overall goal of this thesis was to validate diagnostic tools using a naturally occurring sow lameness model. To address this goal, two research chapters (three and four) focused on four objectives:

1) to determine if behavior assessments, mechanical nociceptive threshold testing and walking and standing lameness scoring could identify a lame sow

2) to determine if behavior assessments, mechanical nociceptive threshold testing and walking and standing lameness scoring were affected by the body system suspected to be contributing to the lameness identified using the Swine Lameness Diagnostic Manual

3) to determine lameness etiology within the suspected body system as guided by the Lameness Diagnostic Manual

4) to evaluate the accuracy of the suspected lameness etiology using the results of the Swine Lameness Diagnostic Manual, standing lameness scoring, locomotion lameness scoring and swine veterinarian expertise.

The objectives of chapter three were to validate standing lameness scoring, locomotion lameness scoring and mechanical nociceptive threshold testing on naturally occurring lameness in sows and gilts. The hypothesis of this study was that these tools could successfully identify a lame sow.

In support of our hypothesis, the results identified that walking and standing lameness scoring systems and sow behavior are promising tools for a producer to use on farm to identify a lame sow.

However, while mechanical nociceptive threshold testing was successful at detecting lameness, the behavior assessments, mechanical nociceptive threshold testing and walking and standing lameness scoring were less correlative when evaluating the body system suspected to influence lameness.

There were two factors that may have influenced the results of the animals' nociceptive threshold during this study. First, the pressure was applied by the PA at a focal and consistent location on the limbs of all animals. The withdrawal response by the animal may have been influenced by the location of the issue causing the lameness. For example, we would expect variation in response to pressure applied near the coronary band on an animal with osteochondrosis at the stifle, compared to an animal with an injury on the distal limb. The location of the injury may also influence the animals' desire to withdraw the affected limb, arbitrarily heightening the kilograms of force tolerated by the animal. Second, the withdrawal response on the sound limb may have also been influenced by the animals' resistance to put weight on the affected limb.

Future research considerations may include performing behavioral observations in the animals' farm environment. While the laboratory obstacles were designed to simulate common obstacles found on farms, there are many environmental factors that could not be replicated. These factors include noises such as those from other animals and farm equipment, as well as smells, and sights, that may influence the speed an animal travels from point A to B. This would improve our understanding about the affect the animals' environment has on the time and interventions required to move lame and non-lame animals. Secondly, testing the utility of mechanical threshold testing in field settings and evaluating the level of agreement when used by different farm employees on sows with known lameness etiologies would provide useful information.

The objective of chapter four was to test the utility of the Swine Lameness Diagnostic Manual on natural lameness cases in sows and gilts. The hypothesis of this study was that the Swine Lameness Diagnostic Manual could successfully diagnose lameness etiologies in naturally lame sows and gilts.

In support of our hypothesis, The Swine Lameness Diagnostic Manual was able to identify a lameness etiology for each case.

Contrary to our hypothesis, the success rate of the manual diagnosis was lower than expected at 4.3% unanimous agreement.

A pitfall of chapter four included evaluation of all lameness cases by a single veterinarian. Factors that may have consistently influenced the findings during the antemortem examination were the veterinarian’s physical examination process, interpretation of antemortem findings, and level of production experience. Ultimately, the success of the Manual diagnosis was dependent on the choices of a single veterinarian performing the antemortem examinations. Future considerations may include having multiple veterinarians use the Lameness Diagnostic Manual during antemortem examinations. This may provide more confidence in findings that are consistent between observers as well as insight into the repeatability of tool’s diagnoses with different users. A second limitation to the Manual evaluation included the absence of pathologists’ input during the post mortem evaluation. The expertise of a pathologists would have helped with the interpretation of the significance of gross findings. Ultimately, the post mortem findings were evaluated and recorded by multiple study personnel with varying levels of experience. Finding that were recorded by these personnel were presented to the panel of three veterinarians evaluating the success of the manual. Involvement by a pathologist during the post mortem evaluations may have influenced the information presented to the veterinarians. However, the decision trees were designed to help veterinarians rule out differentials that could be evaluated based on history, observation, or gross observation before submitting samples for diagnostic testing. Even with an unsuccessful final diagnosis, the veterinarians are likely able to rule out many in the process, making it a useful resource.

Future direction for the Swine Lameness Diagnostic Manual may include modifications to the format to allow for consideration of etiologies based on anatomical location vs. body system. The questions asked of the veterinarian would be more focused on etiologies that affect the distal limb vs. all potential etiologies that affect the pig's musculoskeletal system as an example.

The overall goal of this work was to provide veterinarians and farm employees with resources to identify and diagnose lameness cases in the field. The authors of this work determined that walking and standing lameness scoring could identify sows that had an underlying cause of lameness. Though there was only a 4.3% unanimous successful agreement between practicing swine veterinarians and the identified lameness etiology using data from the Swine Lameness Diagnostic Manual, the diagnostic and gross findings collected during this investigation provided useful information. Based on the consistency of some observations between lame and non-lame animals, veterinarians should interpret findings associated with lameness cases carefully. Further, observation and imaging of the feet allowed for the development of the Swine Foot Image Library.

As previously discussed, there are two critical steps to managing a lameness case, timely detection and an accurate diagnosis. The results from this study provided advancements in both areas.

References

Abell, C., Johnson, A., Karriker, L., Rothschild, M., Hoff, S., Sun, G., . . . Stalder, K. (2014). Using classification trees to detect induced sow lameness with a transient model. *Animal, 8*(6), 1000-1009. doi:10.1017/S1751731114000871

Abiven N, Seegers H, Beaudeau F, Laval A, Fourichon C. Risk factors for high sow mortality in French swine herds. Prevent Veterinary Medicine 1998;33(1–4):109–19. 15.

Anil, S. S., Anil, L., Deen, J. 2005. Evaluation of patterns of removal and associations among culling because of lameness and sow productivity traits in swine breeding herds. Journal of the American Veterinary Medical Association, 226: 956-961.

Bertholle CP, Meijer E, Back W, Stegeman A, Van Weeren PR, Van Nes A. A longitudinal study on the performance of in vivo methods to determine the osteochondrotic status of young pigs. BMC Vet Res(2016) 12:62.10.1186/s12917-016-0682-z

Bonde M, Rousing T, Badsberg JH, Sørensen JT. Associations between lying-down behaviour problems and body condition, limb disorders and skin lesions of lactating sows housed in farrowing crates in commercial sow herds. Livestock Production Science 2004;87(2):179–87.

Boyle, L., F.C. Lenard, B. Lynch and P. Brophy. 1998. Sow culling patterns and sow welfare. Ir. Vet. J. 51:354-357.

Butters-Johnson, A. K., K. J. Stalder, S. Millman, L. A. Karriker and J. Coetzee. 2011. Developing validated and objective industry-ready tools to assess joint pain manifestation and lameness in the sow. United States Department of Agriculture. National Institute of Food and Agriculture. Accessed May 28, 2020. Available at: https://reeis.usda.gov/web/crisprojectpages/0225047-developing-validated-and-objective-industry-ready-tools-to-assess-joint-pain-manifestation-and-lameness-in-the-sow.html [reeis.usda.gov]

Cador C, Pol F, Hamoniaux M, Dorenlor V, Eveno E, Guyomarch C, et al. Risk factors associated with leg disorders of gestating sows in different group-housing systems: a cross-sectional study in 108 farrow-to-finish farms in France. Preventive Veterinary Medicine 2014;116(1–2):102–10.

de Koning DB, van Grevenhof EM, Laurenssen BFA, Ducro BJ, Heuven HCM, de Groot PN, et al. Associations between osteochondrosis and conformation and locomotive characteristics in pigs. Journal of Animal Science 2012;90 (13):4752–63.

Dewey CE, Friendship RM, Wilson MR. Clinical and postmortem examination of sows culled for lameness. Canadian Veterinary Journal 1993;34(9):555–6.

Engblom, Linda & Eliasson-Selling, Lena & Lundeheim, Nils & Belák, Katinka & Andersson, Kjell & Dalin, Anne-Marie. (2008). Post mortem findings in sows and gilts euthanised or found dead in a large Swedish herd. Acta veterinaria Scandinavica. 50. 25. 10.1186/1751-0147-50-25.

Fick, Meghan Elizabeth, "Anatomical characterization of the porcine hoof capsule" (2014). Graduate Theses and Dissertations. 14143. https://lib.dr.iastate.edu/etd/14143

Grégoire J, Bergeron R, D'Allaire S, Meunier-Salaün M-C, Devillers N. Assessment of lameness in sows using gait, footprints, postural behaviour and foot lesion analysis. An International Journal of Animal Bioscience 2013;7(7):1163–73.

Heinonen M, Peltoniemi O, Valros A. Impact of lameness and claw lesions in sows on welfare, health and production. Livestock Science 2013;156(1):2–9.

Heinonen M, Oravainen J, Orro T, Seppä-Lassila L, Ala-Kurikka E, Virolainen J, et al. Lameness and fertility of sows and gilts in randomly selected loose-housed herds in Finland. Veterinary Record 2006;159(12):383–7.

Jensen TB, Bonde MK, Kongsted AG, Toft N, Sørensen JT. The interrelationships between clinical signs and their effect on involuntary culling among pregnant sows in group-housing systems. An International Journal of Animal Bioscience 2010;4(11):1922–8.

Jorgensen B, Andersen S. Genetic parameters for osteochondrosis in Danish Landrace and Yorkshire boars and correlations with leg weakness and production traits. Animal Science 2000;71(3):427–34.

Karriker, L., Abell, C., Pairis-Garcia, M., Holt, W., Sun, G., Coetzee, J., Johnson, A., Hoff, S., Stalder, K. Validation of a lameness model in sows using physiological and mechanical measurements, *Journal of Animal Science*, Volume 91, Issue 1, January 2013, Pages 130–136, https://doi.org/10.2527/jas.2011-4994

Karriker, L., Schwartz, K., Madson, D., Crawford, K., Bates, J., Farron, B., Skoland, K. 2014. Swine Lameness Diagnostic Manual. Iowa State University College of Veterinary Medicine.

KilBride AL, Gillman CE, Green LE. A cross-sectional study of the prevalence of lameness in finishing pigs, gilts and pregnant sows and associations with limb lesions and floor types on commercial farms in England. Animal Welfare 2009;18:215–24.

Kirk RK, Svensmark B, Ellegaard LP, Jensen HE. Locomotive disorders associated with sow mortality in Danish pig herds. *J Vet Med A.* 2005;52:423–428.

Knauer, Mark & Stalder, Kenneth & Karriker, Locke & Baas, Tom & Johnson, Colin & Serenius, Timo & Layman, L & Mckean, James. (2007). A descriptive survey of lesions from cull sows harvested at two Midwestern US facilities. Preventive veterinary medicine. 82. 198-212. 10.1016/j.prevetmed.2007.05.017.

Lundeheim N. Genetic analysis of osteochondrosis and leg weakness in the Swedish pig progeny testing scheme. Acta Veterinaria Scandinavica 1987;37(2):159–73.

Main DCJ, Clegg J, Spatz A, Green LE. Repeatability of a lameness scoring system for finishing pigs. Veterinary Record 2000;147(20):574–6.

Meijer, Ellen et al. “Pressure mat analysis of naturally occurring lameness in young pigs after weaning” BMC veterinary research vol. 10 193. 20 Aug. 2014, doi:10.1186/s12917-014-0193-8

Mohling, C. M., A. K. Johnson, J. F. Coetzee, L. A. Karriker, K. J. Stalder, C. E. Abell, H. 2014. Evaluation of mechanical and thermal nociception as objective tools to measure painful and nonpainful lameness phases in multiparous sows. Journal of Animal Science, 92:3073-3081

Mohling CM, Johnson AK, Coetzee JF, Karriker LA, Abell CE, Millman ST, et al. Kinematics as objective tools to evaluate lameness phases in multiparous sows. Livestock Science 2014;165:120–8.

Nalon E, Conte S, Maes D, Tuyttens FAM, Devillers N. Assessment of lameness and claw lesions in sows. Livestock Science 2013;156(1):10–23.

Newman SJ, Rohrbach BW, Wilson ME, et al. Characterization of histopathologic lesions among pigs with overgrown claws. J Swine Health Prod. 2015:23(2):91-96.

Pluym, Liesbet & Maes, Dominiek & Vangeyte, Jürgen & Mertens, Koen & Baert, Jeroen & Van Weyenberg, Stephanie & Millet, Sam & Van Nuffel, Annelies. (2013). Development of a system for automatic measurements of force and visual stance variables for objective lameness detection in sows: SowSIS. Biosystems Engineering. 116. 64-74. 10.1016/j.biosystemseng.2013.06.009.

Pluym L, Van Nuffel A, Dewulf J, Cools A, Vangroenweghe F, Van Hoorebeke S, et al. Prevalence and risk factors of claw lesions and lameness in pregnant sows in two types of group housing. Veterinární Medicína 2011;56(3):101–9.

Rossow, Kurt. (2010). Porcine Arthropahy/Lameness. NAVC Conference.

Schenck EL, Marchant-Forde DJN. Sow Lameness and Longevity. Sow welfare fact sheet. USDA Livestock behavior and research unit; 2010 [cited 16 April 2018]. Available from: URL: https://www.ars.usda.gov/ARSUserFiles/50201500/ Sow%20Lameness%20 Fact%20Sheet.pdf.

Soltész, Angéla. (2012). Investigation Of The Effect Of Flooring On The Living Performance Of Sows Using Survival Analysis. Applied Studies In Agribusiness And Commerce. 6. 102-104. 10.19041/Apstract/2012/5/17.

Supakorn, C., J. D. Stock, E. Garay, A. K. Johnson and K. J. Stalder. 2018. Lameness: a principle problem to sow longevity in breeding herds. CAB Reviews. 13:1-14. http://www.cabi.org/cabreviews [cabi.org]

Stalder, Kenneth & Knauer, Mark & Baas, Tom & Rothschild, M & Mabry, John. 2004. Sow Longevity. Pig News and Information. 25. 53-74.

Stavrakakis S, Guy JH, Syranidis I, Johnson GR, Edwards SA. Pre-clinical and clinical walking kinematics in female breeding pigs with lameness: A nested case-control cohort study. Vet J. 2015 Jul;205(1):38-43. doi: 10.1016/j.tvjl.2015.04.022. Epub 2015 Apr 23.

Sun, G., Fitzgerald, R., Stalder, K., Karriker, L., Johnson, A., Hoff, S. Development of an Embedded Microcomputer based Force Plate System for Measuring Sow Weight Distribution and Detection of Lameness. Applied Engineering in Agriculture 27, no. 3 (2011): 475–482.

Tinkle AK, Duberstein KJ, Wilson ME, Parsley MA, Beckman MK, Torrison J, et al. Functional claw trimming improves the gait and locomotion of sows. Livestock Science 2017;195:53–7.

Transport Quality Assurance. Des Moines, IA. https://www.pork.org/certifications/transport-quality-assurance/

Traulsen I, Breitenberger S, Auer W, Stamer E, Müller K, Krieter J. Automatic detection of lameness in gestating group-housed sows using positioning and acceleration measurements. An International Journal of Animal Bioscience 2016;10(6):970–7.

Van Amstel, A. 2010. Practical Understanding of Claw Lesions. Feet First Sow Lameness Symposium II, Minneapolis, MN.

Ytrehus B, Andreas Haga H, Mellum CN, Mathisen L, Carlson CS, Ekman S, et al. Experimental ischemia of porcine growth cartilage produces lesions of osteochondrosis. Journal of Orthopaedic Research 2004;22(6):1201–9.

Ytrehus B, Carlson CS, Ekman S. Etiology and pathogenesis of osteochondrosis. Veterinary Pathology 2007;44(4):429–48.